Study on the Methodology of Assessing Accident Risk Costs for Nuclear Power Plants

Yuji Matsuo*

Summary

This paper summarized past estimations of nuclear accident risk costs in Japan and other countries and made relevant discussions. So far, two methods have been proposed for calculating nuclear accident risk costs. One computes an expected damage based on the frequency of accidents and damage values. The other calculates a unit cost by assuming and discounting reserves accumulated in a certain period of time that is not literally linked to the accident frequency. The former is conceived as more appropriate from the viewpoint of public burden assessment. A major problem in this respect is the uncertainty about the accident frequency assessment. This paper considered the problem while referring to earlier studies including assessment methods employing Bayesian statistics.

1. Introduction

In late 2011 after the Fukushima Daiichi Nuclear Power Station accident, the government-organized Costs Analysis Committee assessed costs for various power generation types including nuclear generation anew. As a result, the committee estimated the unit cost for nuclear power generation at 8.9 yen/kWh or more but fell short of finalizing the estimate for the reason that an accident damage value for the Fukushima accident had not been fixed. Specifically, the committee estimated that the unit accident risk cost, which accounts for 0.5 yen/kWh of the total unit cost of 8.9 yen/kWh, may rise by 0.09 yen/kWh as the accident damage value increases by 1 trillion yen from the assumed level of 5.8 trillion yen1). The Power Generation Cost Analysis Working Group, created under the Advisory Committee for Natural Resources and Energy in 2015, followed the Costs Analysis Committee approach, estimating that the unit accident response cost comes to 0.3 yen/kWh, with the total accident damage at 9.1 trillion yen, and may rise by 0.04 yen/kWh as the total damage increases by 1 trillion yen.

In fact, elements that are not finalized for these projections are not limited to the nuclear accident damage. The method for calculating the accident risk unit cost was tentative. The costs for other power generation types are also tentative, as various costs including the grid stabilization cost for renewable energy power generation were left unassessed or tentative.

Most of these uncertain costs are called “external costs3).” While power plant construction, operation and maintenance costs and fuel costs are booked as spending at electric utilities and reflected in market electricity prices, “external costs,” though affecting taxpayers through fiscal spending or unfavorable environmental effects, fail to be booked as their spending or directly reflected in market prices. In some countries, particularly European nations, attempts have been made to assess these external costs. A noteworthy point in this respect is that many European and U.S. studies have sought to comprehensively assess not only the accident risk cost but also other external costs for all electricity sources. This may be natural as far as cost assessment is designed to estimate electricity sources’ relative advantages.

As noted in the previous paper4), the power generation costs that can clearly be defined are the “narrowly defined” costs that electricity utilities pay when generating electricity (or the unit cost that is computed by dividing total costs by power generation output). Under this definition, the accident risk cost corresponds to an insurance premium paid by business operators and is far smaller than other power generation costs. The assessment of external costs including the accident risk cost becomes relevant, only when broadly defined power generation costs are assessed for the whole of a country or the whole of human beings. The assessment of “broadly defined power generation costs” is not easy. First, it is almost impossible to correctly assess the whole of broadly defined costs that range very wide, although Europe and the United States have traditionally tried to make best guesses, as noted above. Second, costs are meaningful only when cost payers and receivers are

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* Senior Economist, Energy Data and Modelling Center, Institute of Energy Economics, Japan

clarified. No clear standard has been given, for example, about how to treat differently domestic wealth transfers such as the provision of nuclear plant location subsidies and external wealth transfers including fossil fuel imports.

Given the current situation, attempts to assess broadly defined power generation costs are still in the initial phase. This paper, while recognizing this point, focuses on the accident risk cost as part of external costs, summarizes earlier assessments mainly in Europe and attempts to analyze how this problem should be conceived in Japan. How the accident risk cost would be positioned in the assessment of overall power generation costs will have to be considered in a separate study.

2. Past studies on assessing the accident risk cost

This section presents an overview of the accident risk cost concept at the Japanese government's Power Generation Cost Analysis Working Group before outlining similar assessment cases in Europe.

2-1 Assessment by the Japanese government

The estimation1) by the Costs Analysis Committee in 2011 estimated Fukushima Daiichi Nuclear Power Station damage at more than 5.8 trillion yen as far as found out then. Based on reports by Tokyo Electric Power Co. and the Ministry of the Environment, the committee assessed costs for decommissioning nuclear reactors, paying damages, decontaminating radiation-exposed areas and other measures.

Next, the committee made an estimation based on the concept of mutual aid. Accident damages were divided by the payment period and annual power generation output to compute the unit accident risk cost. Specifically, the payment period was put at 40 years and annual power generation output at 288 TWh, equivalent to Japan's nuclear power output in 2010, resulting in a unit cost of more than 0.5 yen/kWh (5.8 trillion yen / 40 years / 288 TWh). The unit cost was projected to rise by 0.09 yen/kWh as the damage value increases by 1 trillion yen from the initial estimate of 5.8 trillion yen.

One reason for the adoption of such assessment approach was that the committee had recognized that it would be difficult to assess the accident risk cost as an "expected cost" (accident frequency multiplied by accident damage value). The committee attempted to assess the accident frequency, as indicated by Table 2-1. However, committee members were divided over what expected cost value would be appropriate or whether all expected cost values would be inappropriate. Some doubted if it would be appropriate to use the expected cost for assessing the risk for a low accident frequency and a high damage value. Eventually, the committee did not use the accident frequency explicitly for assessing the accident risk cost. Instead, it gave a calculation based on the concept of mutual aid, although the final value was the same as the expected cost for the frequency of one accident per 40 years as assessed without discounting.

In 2015, the Power Generation Cost Analysis Working Group updated the estimates based on the latest information under the same approach as above. First, the working group raised the estimate of damage from one accident to 9.1 trillion yen in consideration of costs found since 2012 to address the Fukushima accident. In the revision, the panel also estimated that 60.1 billion yen per reactor would be required for additional safety measures to meet new regulatory requirements. One panel member asserted that a decline in the accident frequency should be taken into account as far as such massive additional safety measures are required. Working group members, however, failed to reach any complete agreement on this point. The group concluded that the projection should be based on the frequency of one accident per 4,000 reactor-years in consideration of a sensibility analysis of the probabilistic risk assessment (PRA), which found that one additional safety measure could almost halve the accident frequency. Specifically, the working group estimated the unit accident risk cost at 0.3 yen/kWh by dividing the damage value of 9.1 trillion yen by annual power generation (at 7.06 TWh) for a model plant and 4,000 reactor-years. It also projected the unit cost to rise by 0.04 yen/kWh as damage increases by 1 trillion yen. However, the validity of the 4,000 reactor-years has failed to be clarified and should be continuously studied for appropriate assessment.

Table 2-1 Accident frequency assessment cases

Accident frequency, per reactor-year	Description
1.0×10^{-5}	The frequency is based on the safety target of the International Atomic Energy Agency (IAEA) on early massive radiation from existing reactors. Reflecting lessons learned from the Fukushima accident, the severe accident frequency for reactors to be built in the future is assumed to achieve at least the IAEA safety target.
2.1×10^{-4}	The frequency is based on three accidents and the total operating experience of commercial reactors in the world. As the accident of Units 1 to 3 at the Fukushima Daiichi Nuclear Power Station was triggered by the massive tsunami in the Great East Japan Earthquake, it is counted as one major accident. The other two are the Three Mile Island Unit 2 and Chernobyl Unit 4 accidents. Using this frequency assumes the case where reactors of the same type as at the Fukushima Daiichi Nuclear Power Station would be used without any additional safety measures based on the Fukushima accident experiences.
3.5×10^{-4}	The frequency is based on five accidents and the total operating experience of commercial reactors in the world. The five include the Fukushima Daiichi Units 1 to 3 accidents treated as independent events, as well as the Three Mile Island Unit 2 and Chernobyl Unit 4 accidents. Using this frequency assumes the case where reactors of the same type as at the Fukushima Daiichi Nuclear Power Station would be used without any additional safety measures based on the Fukushima accident experiences.
6.7×10^{-4}	The frequency is based on one accident and the total operating experience of commercial reactors in Japan. The accident of Units 1 to 3 at the Fukushima Daiichi Nuclear Power Station was triggered by the massive tsunami in the Great East Japan Earthquake and is counted as a single event. Using this frequency assumes the case where reactors of the same type as at the Fukushima Daiichi Nuclear Power Station would be used without any additional safety measures based on the Fukushima accident experiences.
2.0×10^{-3}	The frequency is based on three accidents – the Fukushima Daiichi Units 1 to 3 accidents treated as independent events -- and the total operating experience of commercial reactors in Japan. Using this frequency assumes the case where reactors of the same type as at the Fukushima Daiichi Nuclear Power Station would be used without any additional safety measures based on the Fukushima accident experiences.

Source: Costs Analysis Committee 1)

These studies have also recognized that the accident risk is not unique to nuclear power plants. For example, a document for the fourth meeting5) of the Costs Analysis Committee cited the 2010 OECD/NEA assessment6) in regard to accident risk costs for other electricity sources[1]. In the final report, however, the panel failed to provide accident risk costs for electricity sources other than nuclear energy. This may be because Japanese people's concerns had focused on nuclear plant accidents after the Fukushima disaster. This may also be because accident risk costs if based on accident deaths would be minimal except for hydroelectric plants in non-OECD countries where deaths mainly from dam washouts are abundant[2]. From the viewpoint of consistency, however, accident risk costs including deaths should be estimated for all electricity sources.

2-2 European assessments

Detailed studies on the so-called external costs for nuclear and other power generation types have traditionally been conducted in Europe and the United States. As part of such costs, the accident risk cost has been assessed. The following explains European cases:

2-2-1 OECD/NEA 2003

In Europe, the European Commission launched the ExternE project in the early 1990s to study external costs7). The project studied a wide range of matters including the release of various pollutants, radiation's economic impacts and health damage, GHG emissions' impacts on climate change, and nuclear and other power plant accident damage. Peculiar to nuclear accidents was the use of an expected damage value for assessment. When the accident frequency is put at P_i and the accident

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[1] Here, costs in terms of deaths are estimated for accidents with five or more deaths between 1969 and 2000. On average for the OECD member countries, the number of deaths per 1 GWy in power generation came to 0.16 for coal, 0.13 for oil, 0.08 for natural gas, 0.003 for hydro and zero for nuclear. On a non-OECD average basis, the number stood at 0.60 for coal, 0.90 for oil, 0.11 for natural gas, 10.3 for hydro and 0.048 for nuclear energy.

[2] If the relatively high cost of 0.16 person/GWy for coal plants on average for the OECD is used with one person's value assumed at 500 million yen, the unit risk response cost will be limited to 0.01 yen/kWh.

damage at C_i in a scenario, the accident risk cost is determined as a combination of multipliers:

$$(\text{Accident risk cost}) = \sum_i P_i \cdot C_i \tag{1}$$

The accident frequency is one per 100,000 reactor-years for a sophisticated nuclear reactor. The probability of the loss of soundness of the reactor containment vessel and massive radiation release, in the case of a core damage accident, i.e. the CDF/LERF ratio as described later, is assumed at 19% according to the U.S. Nuclear Regulatory Commission (NRC) 8). The accident risk cost (i.e., an expected accident damage value per reactor-year) computed in this way is divided by power generation output (i.e., annual output for one nuclear reactor) to determine the unit accident risk cost as part of the unit power generation cost.

The problem with the adoption of such expected damage value is that people do not necessarily act according to the expected value as a benchmark. When I buy automobile liability insurance, my expected cumulative payments may usually be greater than an expected damages payments regarding an automobile accident. My purchase of such insurance even in such case may mean that I prefer highly frequent, smaller losses to lowly frequent, greater losses, even if both losses have the same expected value. When we consider a lowly frequent, very massive loss like a nuclear accident, how to estimate this effect becomes a major problem. The ExternE project report fully recognized the presence of the problem but noted that no attempt to quantify the effect of the problem had been successful and it would have to be made in the future.

A calculation using this method is seen in a report by the Nuclear Energy Agency (NEA), a specialized agency of the Organization for Economic Cooperation and Development (OECD)3). This report assumes the accident frequency at one per 100,000 reactor-years, the direct damage value at 17.1 billion euros and annual power generation at 7 TWh per reactor in France and computes the direct accident damage unit cost as 0.00046 eurocents/kWh. Furthermore, it multiplies the cost by 1.25 to cover indirect economic effects and assumes a premium for a lowly frequent, greater damage value at 20 times, estimating the unit accident risk cost at 0.012 eurocents/kWh. No ground for the 20 times is clarified.

The unit accident risk cost accounts for a relatively small share of external costs for nuclear power generation. As a result of the ExternE project, the report assesses radiation's effects on human health at various phases from uranium mining to final radioactive waste disposal, in the case of normal operation free from any accident. With the discount rate given at 0%, the effects are computed at 0.25 eurocents/kWh in the case of France, much greater than the accident risk cost.

2-2-2 Versicherungsforen Leipzig (2011)

In 2011, Versicherungsforen Leipzig, a private German insurance think tank, released a report9) assessing the accident risk from the viewpoint of insurance for nuclear power generation commissioned by the German Renewable Energy Federation (BEE). In the report, a damage value for a severe accident is estimated before a premium for a lowly frequent, large accident is assessed along with the premium's contribution to the unit nuclear power generation cost.

Based on existing assessments, an accident damage value was estimated with multiple cases assumed for each of multiple items. As for a lethal cancer subject to the highest cost, 20 assessments ranging from 80 billion to 7.5 trillion euros are presented. In the highest cost case, 4.5 million euros would be paid in compensation to each of 1.68 million people. To "reflect the worst case", a weight of 0.5 was given to the highest cost case and a weight of 0.5÷19 to the remaining 19 cases, leading to a weighted average of 4.4 trillion euros. In a similar way, the weighted average accident damage value comes to 5.9 trillion euros against a simple average of 2.5 trillion euros. As shown in Table 2-2, cancer accounts for most of the accident damage value. The assumed 1.68 million deaths indicate an accident that would be far greater than the Fukushima accident. The adequacy of these assumptions, as well as the abovementioned weighting method, may have to be verified.

Table 2-2 Accident damage value estimation for Grohnde Nuclear Power Station (Versicherungsforen Leipzig)

Unit: Billion euros

	Average damage	Weighted average damage
Fatal cancer cases	1,679	4,440
Non-fatal cancer cases	518	756
Genetic damage	33	77
GDP loss in resettlement area	258	595
Food bans	38	38
Evacuation and resettlement	2	2
Total	2,528	5,908

Source: Versicherungsforen Leipzig 9)

Versicherungsforen Leipzig made such assessment for 17 reactors in Germany and approximated a probabilistic distribution of accident damage values with the beta distribution, giving an average damage value at 5.9 trillion with a standard deviation of 0.03 trillion euros. It also proposed the use of the average plus 6 times the standard deviation of the distribution for assessing an insurance premium for the lowly frequent, great damage risk, putting the accident damage value for the estimation at 6.09 trillion euros. It seems strange to assume such a small standard deviation for a very widely fluctuating value like a nuclear accident damage. (In fact, Versicherungsforen Leipzig made the abovementioned lethal cancer estimates with the maximum gap of nearly 100 times.) This may be because they assumed the same data for all items excluding the GDP loss as shown in Table 2-2 for all the 17 reactors and used 17 damage values with differences seen only for the GDP loss for the statistical analysis. Thus the assessment approach may have to be reconsidered.

On the accident frequency, the report gave consideration to such factors as terrorist attacks and computer viruses. However, accident frequency assessment results were not used for calculating the accident risk cost. Instead, they used the same approach as the later-mentioned Cour des comptes assessment and assumed the accumulation of the abovementioned 6.09 trillion euros on the premise of a 2% interest rate and a certain period of time. Then, they computed the annual accumulation and divided it by annual nuclear power generation (140 TWh in Germany in 2010) to determine the unit cost. They noted that assessments would differ depending on whether reserves would be accumulated in a single pool for the 17 existing reactors in Germany or a single pool for each reactor, a total of 17 pools. If reserves are accumulated in a single pool over 100 years, the accumulation's contribution to the unit power generation cost will be 13 eurocents/kWh. If reserves are accumulated in 17 pools over 10 years, the contribution will be 6,730 eurocents/kWh.

2-2-3 Institut de radioprotection et de sûreté nucléaire (IRSN) (2012 and 2013)

France's Institut de radioprotection et de sûreté nucléaire (IRSN) assessed the damage value for a large-scale nuclear accident in France. The figures in a book released in 2012 10) are somewhat different from those in a report in 2013 11).

The accident damage values in the 2013 report are given in Table 2-3. In the report, accident damage values are projected for two cases -- a "grave accident" where a reactor core melts down with radioactive substances released and a "major accident" where a reactor core melts down with one-third of the core's content released in the worst case. The site-related cost in the table covers the elimination and decontamination of the accident site. The contaminated area cost covers the purchase of off-limits areas from their owners and the restoration of radiation-controlled areas to their original state. The total cost also includes the radiological off-site costs, image costs (economic effects on tourism, exports, etc.), effects on power grids (including costs for repairing grid facilities and losses on the decommissioning of nuclear equipment). Characteristically, the image costs account for a fairly large share for both grave and major accidents.

Table 2-3 Accident damage value assessment (IRSN)

Unit: billion euros

	Grave accident	Major accident
Site-related cost		
Rehabilitation cost	5	5
Replacement cost	6	9
Other costs	-	-
Subtotal	10	15
Costs of contaminated areas		
Exclusion zones	-	13
Radiological controlled areas	11	98
Subtotal	11	110
Radiological off-site costs		
Emergency counter-measures	-	3
Sanitary effects	-	10
Psychological effects	0	17
Loss of agro-production	9	14
Relocation cost	0	10
Subtotal	9	54
Image costs		
Lower demand for French agro products	13	60
Lower demand for tourism	25	75
Lower exports of other products	12	46
Subtotal	50	180
Effects on the electricity network	44	88
Total	120	450

Sure: IRSN[11)]

2-2-4 Rabl et al. (2013)

Rabl et al. (2013) estimated and compared external costs for nuclear power generation and its alternative electricity source for the purpose of assessing whether a nuclear plant shutdown would reduce environmental and human health risks[12)]. As an alternative electricity source, they assumed a wind power plant backed up by a natural gas-fired combined cycle (NGCC) plant. The load factor was assumed at 90% for nuclear power generation against 25-35% for the wind power plant. The gap was assumed to be covered by NGCC. Three price cases are assumed for low, central and high levels. As indicated by Table 2-4, the external costs for the alternative electricity source in the central case are estimated at 1.22 eurocents/kWh, higher than 0.79 eurocents/kWh for nuclear power generation.

As part of external costs for the alternative electricity source (wind and NGCC), a GHG emission cost is estimated based on a carbon price assumed at 8.3-75 euros/tCO_2 and a CO_2 emission intensity at 0.5kg/kWh for NGCC. The health damage cost is assumed at 0.2-1.8 eurocents/kWh in accordance with the latest assessment under the ExternE project.

For nuclear power generation, external costs are put at 0.21 eurocents/kWh (central case) under the assumed discount rate of 5%, based on 13). The low price is assumed at one-third of the central price and the high price is three times as high as the central. The external costs include a cost of health damage from radiation accompanying power plant operation, as well as upstream (uranium mining) health damage. The radioactive waste disposal cost is assumed at 0.1-0.3 eurocents/kWh as the part of the Cour des comptes[14)] estimate of 0.3 eurocents/kWh that has failed to be covered by reserve accumulation by business operators.

Table 2-4 External costs for nuclear and alternative electricity sources (Rabl et al (2013))

Unit: Eurocents/kWh

	Nuclear				Alternative electricity source (wind power + natural gas)		
	External cost of current operation	External cost of waste management	External cost of accident	Total	Cost of GHG	Health damage cost	Total
Low	0.07	0.10	0.08	0.25	0.26	0.12	0.38
Central	0.21	0.20	0.38	0.79	0.83	0.40	1.22
High	0.63	0.30	2.29	3.22	2.74	1.31	4.05

Source: Rabl et al.[12)]

The accident damage value for the central case is assessed in the following way: First, one accident is assumed to cause cancer for 10,000 people over 20 years, with one person's value put at 5 million euros. Against a power generation capacity loss of 6 GW, the loss per GW is put at 5 billion euros. As the electricity source is to be lost for 15,000 hours (3,000 hours a year x 5 years), the unit loss comes to 0.2 euros/kWh. The decontamination cost is assumed at 30 billion euros based on an estimate in Fukushima. Some 500,000 residents within a radius of 30 km from the nuclear power plant are assumed to evacuate, with each evacuee costing 500,000 euros. No farm products are assumed to be produced in a 1,000 km^2 area over a century, resulting in a projected annual loss of 75,000 euros/km^2.

Table 2-5 Nuclear accident damage value (Rabl et al (2013))

	Billions euros							Accident risk cost, eurocents /kWh
	Fatal cancers	Lost reactors	Cost of lost power	Cost of cleanup	Cost of displaced persons	Cost of lost agriculture	Total	
Low	10	20	10	20	100	5	165	0.08
Central	18.8	30	18	30	250	7.5	354	0.38
High	50	40	50	200	1,000	50	1,390	2.29

Source: Rabl et al.[12)]

Based on the damage value assumption, Rabl et al. assessed the unit accident risk cost in the following way. First, a large nuclear accident is assumed to occur every 25 years in the world in the middle-price case, based on the interval between the Chernobyl accident in 1986 and the Fukushima accident in 2011. The damage value for one accident given in Table 2-5 is divided by 25 years and global nuclear power generation in 2008 at 2,100 TWh. Then, the future damage value is discounted with the rate of 5% into the current value of 0.38 eurocents/kWh. Similarly, one accident is assumed to occur every 40 years for the low case and every 15 years for the high case. The unit accident risk cost comes to 0.08 eurocents/kWh for the low case and

2.29 eurocents/kWh for the high case. However, these results are given as estimated ranges. Essentially, Rabl et al. noted, the Monte Carlo approach should be used to assess uncertainties to give consideration to a combination of items.

2-2-5 Lévêque (2013) and D'haeseleer (2013)

In a report[15)] released in May 2013, Lévêque said that even if the accident frequency were one per 100,000 reactor-years (100 times as large as assumed by the French plant supplier Areva) with the accident damage value put at 1 trillion euros (10 times as large as the assumed Fukushima accident damage), the unit accident risk cost for a reactor generating 1 TWh per year would be limited to around 1 euro/MWh (0.1 eurocents/kWh). In a report[16)] released in June 2013, Lévêque assessed the accident frequency using Bayesian statistics.

Bayesian statistics uses actual data and some prior information to assess some parameter like the accident frequency of p. If an event emerges five times when a trial is done 100 times today, for example, the event probability estimated through the data will be given as $p = 5 \div 100 = 0.05$. If the event emerged 80 times when I made the trial 1,000 times by yesterday (with the event probability estimated as 0.08), however, the event probability I estimate today would be larger than 0.05 according to the prior information. The event probability based on trials made by yesterday and today would be 85÷1100 = 0.077. New actual data thus lead the event probability to fall slightly from 0.08 assumed by yesterday. In this way, the Bayesian statistics approach generalizes attempts to conduct an appropriate assessment based both on our prior information and new actual data.

What Lévêque did was to assess what the most reliable value is as the "posterior" probability by assuming that we had had a probabilistic risk assessment (PRA) result[3] as a "prior" probability and by being based on information from actual nuclear accident experiences including the Fukushima accident. One reason for such assessment is that the actual accident frequency as actual data is extremely low. In other words, attempts to assess the accident frequency based only on actual accidents fail to be useful as assessment results range wide, as described later. Therefore, it may be natural to try to make an adequate assessment by using other data as well as actual data. Lévêque said we should base any decision on all available data whether they are empirical or theoretical.

What Lévêque used as prior information was the core damage frequency (CDF) assessment result in the NUREG-1560 report by the U.S. Nuclear Regulatory Commission (NRC)[17)]. Details are given in the appendix. According to Lévêque, the past operation of nuclear plants in the world totaled about 14,400 reactor-years (n) with 11 core damage accidents (y) including the Fukushima accident, resulting in the CDF as $y \div n = 7.6 \times 10^{-4}$ per reactor-year. The frequency is some 10 times as high as 6.5×10^{-5} per reactor-year from the PRA (NUREG-1560). Then, Lévêque used NUREG-1560 data to approximate prior distribution (probabilistic distribution of the accident frequency) with the beta distribution and took into account data for the 11 accidents, concluding the posterior accident frequency after Bayesian updating as 3.2×10^{-4} per reactor-year. Given that the improvement of safety through the accumulation of experiences failed to be reflected in the non-Fukushima core damage accidents seen mostly in the initial phase of the nuclear energy use history and that the 11 accidents are assumed as separate ones, however, the conclusion could be an overestimation, Lévêque said.

The Lévêque calculation represented a CDF assessment as noted above, amounting to the so-called Level 1 PRA. In an actual accident, the core damage may be followed by a reactor containment vessel damage leading to a massive radiation release (for a Level 2 PRA). The frequency of Level 2 accidents is called large early release frequency (LERF). In a paper released in 2013, D'haeseleer cited the Lévêque assessment and recommended revisions regarding the following two points[18)]:

- The 11 damage cases include those falling short of leading to grave accidents. Actually, only five cases (one Three Mile Island unit, one Chernobyl unit and three Fukushima units) are qualified for the CDF as defined by the NRC.
- Rather than the CDF, the LERF should be used for accident risk assessment. Generally, the LERF is viewed as one-tenth of the CDF.

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[3] The PRA sets a detailed event tree covering from an event as an accident trigger to a severe accident and a massive radiation release and uses the event tree to quantify an accident probability. It has been continuously studied and evaluated since the 1970s worldwide.

Given the above, D’haeseleer used 5 instead of 11 to compute the posterior CDF probability as 1.7×10^{-4} per reactor-year and multiplied the probability by 0.1 to determine the LERF of “about 2×10^{-5} per reactor-year[4].” Citing the IRSN’s estimation of the major accident value as 430 billion euros in 2012 and assuming one reactor’s annual power generation at 10 TWh, D’haeseleer estimated the unit accident risk cost at 0.086 eurocents/kWh.

Some doubts, however, exist about the projection method and results. If given the CDF probability of $p = 3.2\times10^{-4}$ per reactor-year as indicated by Lévêque, the probability of 11 accidents (used by Lévêque as actual data) or more through operation totaling 14,400 reactor-years may be expressed as $\sum_{k\geq 11} {}_{14400}C_k\, p^k (1-p)^{14400-k}$. The probability thus comes to only 0.8%. Similarly, the LERF of 2×10^{-5} as computed by D’haeseleer is used to estimate the probability of four or more accidents involving massive radiation releases. The result is only 0.02%. Despite the use of actual data, the calculations result in very low probabilities to explain the actual data. This leads us to have doubts about the applied data or the estimation approach. One problem may be the treatment of the Fukushima accident as three independent events[5]. Problems can be conceived regarding how to treat data (as noted by Lévêque, the above approach fails to take into account the recent improvement of safety), as well as the estimation method itself. Despite these problems, the Lévêque and D’haeseleer approaches attempted to assess the accident risk cost from a wider viewpoint while fully recognizing the fundamental problems related to the limit on data. In this sense, the two assessments are differently significant from the other estimation cases.

2-2-6 D’haeseleer (2013)

In 2013, D’haeseleer published a report that comprehensively assessed the economics of nuclear power18). In the report, he outlined seven cases for the accident risk cost, including the abovementioned OECD/NEA, Rabl et al., IRSN and Lévêque assessments. The other three were Torfs (2001)19), NewExt (2004)20) and Institut für Energiewirtschaft und Rationelle Energieanwendung (IER), Universität Stuttgart (2013)21).

Torfs assessed the unit accident risk cost as between 8×10^{-5} and 3.5×10^{-2} eurocents/kWh in Belgium. NewExt assessed the unit accident risk cost as 5.74×10^{-4} eurocents/kWh in non-OECD countries, based on major accidents with five or more deaths (1,221 for coal, 397 for oil, 125 for natural gas, 105 for LPG, 11 for hydro and one for nuclear). The IER assessed unit accident risk costs in multiple scenarios as between 1.3×10^{-5} and 1.5×10^{-2} eurocents/kWh in Germany.

Integrating these assessments, D’haeseleer concluded about 0.1 eurocents/kWh as an appropriate unit accident risk cost, tentatively assuming one-third of the level as the lower limit and three-fold as the upper limit. He also noted that the issue should be studied continuously.

2-2-7 Cour des comptes (2014)

In 2012 and 2014, France’s Cour des comptes published reports that comprehensively assessed nuclear power generation costs in the country14)22). In these reports, Cour des comptes attempted to calculate the unit accident risk cost as one of the costs that are difficult to accurately and quantitatively assess.

As for the accident damage value, Cour des comptes referred to the abovementioned IRSN assessment in 2013. First, Cour des comptes assumed 120 billion euros for a grave accident in Table 2-3 as the accident damage value. Assuming that amount of reserves to be accumulated over a 40-year period for nuclear plant operation with the annual interest rate put at

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[4] Given that the LERF/CDF ratio of 0.1 bypasses Bayesian updating under this approach, the LERF is more appropriate than the CDF for an actual assessment. However, PRA results differ from reactor type to reactor type, making it impossible to compute any generalized value. Therefore, D’haeseleer said, the results from the abovementioned estimation were rounded upwards.

[5] In the probability theory, independent events A and B mean that the p(AB) probability of both A and B occurring is expressed as the product of their respective probabilities p(A) and p(B) -- p(AB)=p(A)p(B). This indicates that the p(B|A) probability of B occurring under conditions for A would be equal to p(B). This does not meet the probability of accidents occurring at Units 1 (A) and 2 (B) of the Fukushima Daiichi Nuclear Power Station. On the contrary, the simultaneous breakdown of three cores statistically indicates that the three events were not actually independent. If the Fukushima accident were to be counted as three events, one unit’s accident probability of p(A) and the conditional probability of p(B|A) might have to be separately estimated, requiring more complex formulation.

5%, it computed the annual provision as 990 million euros. The amount was divided by France's annual nuclear power generation at 410 TWh, resulting in 0.24 eurocents/kWh.

An apparent reason for using the damage value for a grave accident instead of a major accident in the estimation may be that Cour des comptes viewed the probability of a major accident as very low. However, there may be no reason for neglecting the major accident. Anyway, Cour des comptes emphasized that the estimation was tentative and that it did not recommend the estimated amount of reserves to be accumulated.

2-3 Summary of accident risk cost assessments

The abovementioned assessments are summarized in Figure 2-1. These assessments are given in prices for different base years. As base years fail to be clarified for some assessments, however, prices are not adjusted. Given the wide range of assessments any influence of base years may be small. The assessment by the Power Generation Cost Analysis Working Group is cited as a Japanese estimation case. In this respect, the exchange rate of 130 yen to the euro as of May 2015 is adopted.

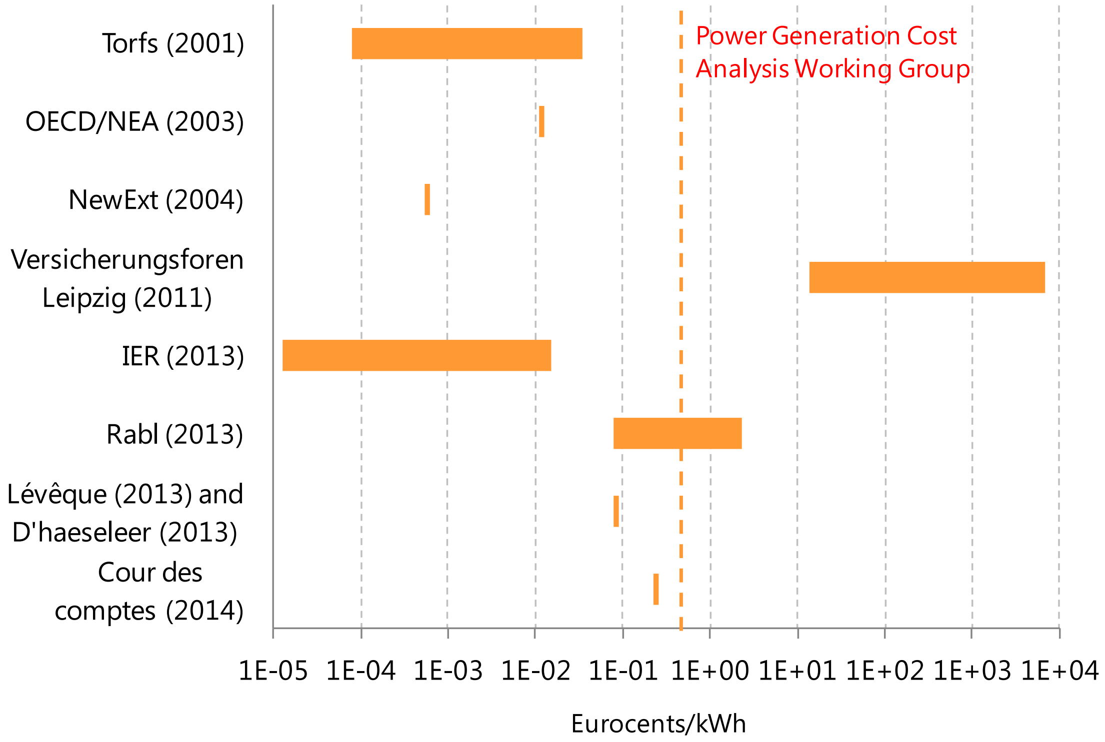

Figure 2-1 Comparison of accident risk cost assessments

As indicated in the above, accident risk cost assessments differ widely. Among assessments for Germany, the largest estimate by Versicherungsforen Leipzig is 500 million times as high as the smallest one by the IER. While unit accident risk cost estimates made before the Fukushima accident were relatively low below 0.1 eurocents/kWh, those projected after the accident, excluding the IER estimate, were relatively high. These estimates thus indicate some trend. The IER assessment used the PRA assessment result of one accident per 0.1-10 million reactor-years as the accident frequency. The authors of the IER report state that these probabilities, obtained through PSA, are not to be questioned because of the Fukushima accident, since it was a clear "design error" or "error in the safety design" 18). In contrast, other assessments given after the Fukushima accident refrained from using PRA results and provided higher accident risk cost estimates.

Figure 2-2 summarizes accident frequency figures used for these assessments. For the assessment cases where some reserve accumulation periods are assumed (10 to 100 years for Versicherungsforen Leipzig and 40 years for Cour des comptes), the inverse of the product of the assumed reserve accumulation period and the number of reactors is given as equivalent to the accident frequency. The assessments here also differ widely. While the OECD/NEA and IER assessments adopting a priori assumptions including PRA results use low frequency figures below one per 100,000 reactor-years, the other assessments, excluding the Versicherungsforen Leipzig report, use frequency figures roughly between one per 1,000 reactor years and one per 100,000 reactor-years.

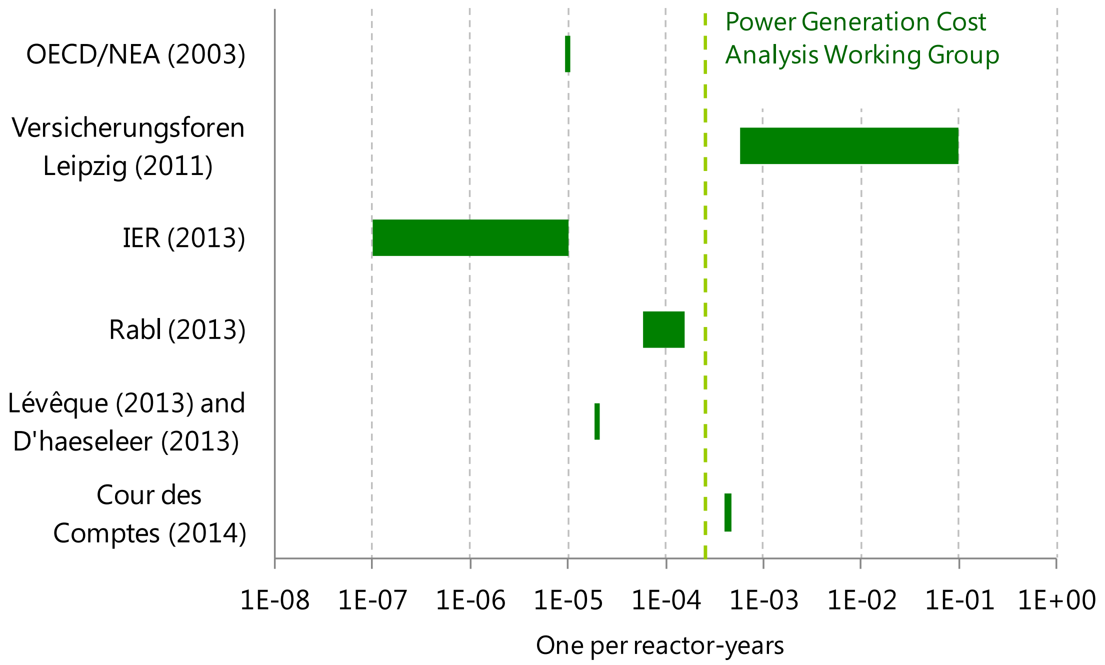

Figure 2-2 Comparison of accident frequency assumptions

3. Discussion on accident risk cost assessment approaches

As indicated above, unit accident risk cost assessments differ widely from expert to expert or from organization to organization. By comparing projection methods and assumptions, however, we can find some guideline for analyzing this issue. First, a clear point is that wide gaps between accident frequency assumptions indicated in Figure 2-2 exert great influences on differences between unit accident risk cost assessments. Accident frequency assumptions are relatively lower for the OECD/NEA and IER assessments using PRA assessments or IAEA safety targets and relatively higher for the Rabl and D’haeseleer assessments using actual data. Particularly special is the Versicherungsforen Leipzig assessment that uses what cannot be viewed as an accident frequency. From this perspective, assessment approaches are discussed below:

3-1-1 Classification of assessment approaches

(1) Expected damage value and reserve accumulation approaches

The assessments outlined in Chapter 2 use two different approaches for computing unit accident risk costs.

①”Expected damage values” approach

These kinds of approaches usually use an expected damage value into which a damage value for an accident is multiplied by an accident frequency. Here, the accident value and frequency, or the accident probability distribution, must be appropriately assessed. How the premium for a lowly frequent, great damage risk should be assessed, as described in Section 2-2-1, is always cited as a question.

②“Reserve accumulation” approach

Even if the nuclear accident frequency is one per 1,000 years, an accident may not necessarily occur in 1,000 years.

It may occur in 10 years or 50 years. The approach using reserve accumulation sets an annual provision to accumulate reserves equivalent to an accident damage value by a target year irrespective of an accident frequency and divides the annual provision by annual power generation output to determine a unit provision amount. In the abovementioned assessment, France's Cour des comptes assumed the reserve accumulation period at 40 years equivalent to the service life of a nuclear reactor, while Versicherungsforen Leipzig put the period at 10 years or 100 years. As a matter of course, such assessment is made only for a case where the average interval between accidents is significantly longer than the reserve accumulation period. If not, an accident could occur several times within the reserve accumulation period, making reserve accumulation meaningless.

The second approach was taken by Cour des comptes and Versicherungsforen Leipzig. The first one was adopted by most of the others. There is a conceptual difference between the two approaches. Under the first approach, an accident is assumed to occur potentially at some probability "at the same time" as the cost arises. Under the second approach, there is a time gap between the commencement and completion of reserve accumulation. Under the first approach, an accident damage value is generally multiplied by an accident frequency. Under the second, some discount rate must be used to discount a future cost into a current value. Or some interest rate must be used for calculating compound interest. Actually, the interest rate of 5% is used by Cour des comptes and the rate of 2% by Versicherungsforen Leipzig.

Taken as rather special is the Rabl et al. assessment. It uses the discount rate of 5% for projection. However, there is no explanation such as that reserves will be accumulated in preparation for an accident that could occur once in 25 years. Rather, the Rabl et al. paper says that an accident will occur at a certain annual probability from the starting year. On the contrary, the Costs Analysis Committee and the Power Generation Cost Analysis Working Group said that their assessments were based on the "concept of mutual aid" close to the second approach. However, they divided a damage value by power generation output to determine an accident risk cost *without* taking any interest rate calculation into account. The first and second approaches are classified depending on whether an actual or PRA accident frequency or a reserve accumulation period is used or whether interest or discount rates are used for calculation. We must note, however, that in some cases an estimation classified as the first category explains itself as calculating reserve accumulation, and vice versa.

Among assessments given in Figure 2-1, the Versicherungsforen Leipzig, Cour des comptes and Rabl et al. assessments indicating relatively higher unit accident risk costs adopt the second approach (at least using discount rates for computation), while the others use the first approach. This may be natural because reserve accumulation periods assumed for the first approach are generally shorter than the average interval between accidents. However, it may be needless to say that assessment results depend on accident frequency, reserve accumulation period and accident value assumptions, rather than on estimation methods.

(2) Which approach is adequate?

The largest factor behind the 28,000-fold gap between the Cour des comptes and (maximum) Versicherungsforen Leipzig assessments among those adopting the second approach may be the 51-fold gap between their accident damage value assumptions. There are also a 5.5-fold gap in reserve accumulation periods (40 and 10 years), a 2.0-fold gap in interest or discount rates (5% and 2%), a 2.9-fold gap in annual power generation output (410 TWh in France and 140 TWh in Germany) and a 17-fold gap regarding the number of pools. Accident damage value assumptions for both assessments have problems, as described above, and both can afford to make efforts for more appropriate estimations. Meanwhile, the problem is the difference in reserve accumulation periods. Even if the lower interest rate of 2% is assumed, the unit cost for the reserve accumulation period of 40 years is five times more than for 100 years. That for 10 years is 29 times more than for 100 years.

A key point to watch out for is that while the difference in accident value assumptions is attributable to a gap in the accuracy of assessment, the 5-fold or 29-fold gap comes only from different reserve accumulation systems. As noted in the previous paper4), the "broadly defined power generation costs" including external costs should cover only costs required due to the characteristics of relevant technologies and exclude those required for social, political and other factors[6]. From this

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[6] This can be understood from the viewpoint that power generation cost assessments are politically used primarily for selecting a future

perspective, accident risk cost estimates assessed under the reserve accumulation approach are not peculiar to the technology of nuclear energy but depend on reserve accumulation systems and should not be included into broadly or narrowly defined power generation costs.

There are other reasons why it is not appropriate to consider assessments under the reserve accumulation approach as part of broadly defined power generation costs (the national burden regarding accident risks). There are three points to make here. First, the Versicherungsforen Leipzig assessment was made for the purpose of calculating an insurance premium. However, the insurance premium calculation and the national burden assessment are separate from each other and should not be confused. Assume that reserves will be accumulated over 10 years in line with the Versicherungsforen Leipzig assessment and that the probability of an accident being absent over the 10 years is considerably greater than that of an accident occurring within the period. If any accident did not occur in 10 years, reserves equivalent to an accident damage value would have been accumulated. Then, a decision may be required on whether reserve accumulation should be continued further. If reserve accumulation were discontinued then, no accident risk cost would be imposed for later nuclear power generation. Thus, in terms of average provisions for a longer reserve accumulation period, the same cost as assessed under the expected damage cost value approach would be imposed. If the accident risk cost is assessed as an insurance premium, accumulated premium payments may become profit for insurance companies taking risks and similar accumulation may be continued in the 11th and later years. If reserve accumulation is made on a national basis, however, this does not stand. If the national burden caused by potential nuclear accidents is at issue, the accident risk cost assessment should be based in principle on an expected damage value that can be scientifically estimated.

Second, it may be ordinary in general to conceive that as the number of nuclear power plants in operation rises, accident risks and the accident risk cost will proportionately increase. Under the reserve accumulation approach, however, this may not be the case. As given in the Versicherungsforen Leipzig assessment, the cost will depend simply on the assumed number of pools. Third, the reserve accumulation approach does not use any accident frequency. This means that the accident risk cost will remain unchanged however safety measures are improved to reduce the accident frequency.

Given the above, the first “expected value” approach should be regarded as more appropriate than the second “reserve accumulation” approach as far as the national burden is at issue. The problems then will be how to assess the accident damage value and accident frequency and how we should treat the lowly frequent, great damage that is characteristic of a nuclear accident. These problems are discussed in the following section.

3-1-2 Expected damage value approach and accident frequency assessment

As explained above, the expected damage value approach essentially determines the unit accident risk cost based on an accident damage value and an accident frequency. The problem is that it is difficult to assess the value and frequency. Unless they are assessed in some way, however, the accident risk cost cannot be assessed.

Regarding accident damage values, the Costs Analysis Committee has assessed and used a damage value for the Fukushima accident. Based on additional information, the assessment may be updated. It should also be noted that the damage of a future accident would not be exactly the same as that of the Fukushima accident. MACCS2[23)], COSYMA[24)], OSCAAR[25)] and other computational codes have been developed to assess the so-called externality including nuclear accidents, making it possible to assess a generalized accident value. Essentially, it is desirable to use the Fukushima accident value as a sample for improving these computational codes and assess a generalized accident value anew on appropriate conditions.

Even more serious is the problem of accident frequency assessment. The accident frequency assessment is far more uncertain than the accident damage value assessment as given in Figure 2-2. The following considers this point.

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electricity mix. A power generation technology that naturally has high cost due to its characteristics should be avoided. If a power generation technology has high cost due to social and other factors rather than its characteristics, however, the possibility of such factors being eliminated should be taken into account first. For the electricity mix selection purpose, “power generation costs” arising from power generation technologies should be separated from other costs for assessment. For example, attention should be paid to the point that additional costs for promotion of the feed-in-tariff system are separate from solar or other “power generation costs” and should be positioned as the national burden imposed to cover an appropriate profit added to power generation costs.

(1) Uncertainty of accident frequency assessment

Accident frequency figures given as IAEA safety targets and PRA results give some standards for actual accident probability rates. Rather, the PRA is almost the only method with which we can reasonably assess the accident probability. The accuracy of this method should be improved further for more adequate assessment.

However accurate PRA results are, they are model estimation results that must be checked against actual data. Therefore, it may be natural to determine an accident frequency based on the limited accident cases of Fukushima in Japan and Chernobyl and TMI in the rest of the world and accumulative nuclear reactor operation years in Japan or the world. Concern for everyone here may be the scarcity of actual accident cases. Given the following simple consideration, the concern may turn out to be appropriate.

According to the IAEA, total operating experience of nuclear power as of December 31, 2013, stood at 1,646 reactor-years in Japan and 15,661 reactor-years in the world26). Despite the fact that no nuclear reactor was in operation in Japan in December 2014 after all Japanese reactors were shut down following the Fukushima accident, however, even years during the shutdown are considered regular inspection periods and included into operation years. If years after their shutdown in the wake of the Fukushima accident are excluded, operation years come to 1,460 reactor-years. In the following computation, 1,460 reactor-years are used as Japan's accumulated nuclear plant operation years. The world's operating experience is reduced by the same gap to 15,470 reactor-years.

In Japan, a Fukushima-class accident occurred once in 1,460 reactor-years[7]. In this case, the accident frequency is computed as 6.8×10^{-4}/reactor-year with the inverse adopted. If three accidents are assumed for the world[8], similarly, the accident frequency is computed as 1.9×10^{-4}/reactor-year (a small gap with Table 2-1 emerges as the nuclear plant shutdown following the Fukushima accident is taken into account for Japan while operation years after 2011 are counted for the world).

If the accident frequency of 6.8×10^{-4}/reactor-year for Japan is used along with the power generation capacity of 1.2 GW, the load factor of 70% and the accident value of 5.8 trillion yen as adopted by the Costs Analysis Committee in 2011, the unit accident risk cost comes to about 0.54 yen/kWh without discounting, almost consistent with the estimate of the committee[9]. However, the real accident frequency could be lower and the accident could have occurred by chance. Or, the frequency could be higher and the accident could have fortunately been limited to one in 1,460 reactor-years. The classical Clopper-Pearson confidence interval of 95% comes to 1.7×10^{-5}-3.8×10^{-3}/reactor-year for an accident that occurred once in 1,460 reactor-years. There is a 200-fold gap between the upper and lower limits, resulting in the unit accident risk cost of 0.01-3.0 yen/kWh.

How to interpret such wide gap depends on how to use the assessment for comparison. If according to the estimation by the Costs Analysis Committee, the unit nuclear power generation cost stands at 8.4 yen/kWh excluding an accident risk cost. If the above accident risk cost is added, the result comes to 8.4-11.4 yen/kWh. As far as according to this estimation, the unit nuclear power generation cost including the accident risk can be concluded as lower than the minimum estimate of 12.1 yen/kWh (in 2030 for a case where prices are expected to decline) for solar photovoltaics. However, it is wrong to assert the result as higher than the unit coal power generation cost of 9.5 yen/kWh in 2010. In fact, no conclusion can be given on such comparison. In general, such estimated wide range should be viewed as useless[10,11].

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[7] If the Fukushima Daiichi Nuclear Power Station is viewed as having had three accidents for Units 1 to 3, an equation using a conditional probability may have to be formulated as explained above. In this case, different assumptions for the accident damage value as well as the accident probability may be required for the single Fukushima accident and the three individual accidents. As far as it is impossible to accurately assess the accident frequency for a single reactor, any more detailed probability argument may not be significant. Anyway, the frequency of an accident occurring on some condition in Japan should be assessed based only on one case representing the entire Fukushima accident.

[8] Assumed here are the 1971 Three Mile Island accident, the 1986 Chernobyl accident and the 2011 Fukushima accident. In fact, the containment vessel fell short of being damaged in the TMI accident and the damage value for the TMI accident was one or two orders smaller than for the Chernobyl accident27). Therefore, the advisability of comparing these accidents is doubtful. Here, however, three accidents including the TMI event are counted tentatively.

[9] As an assessment by the Power Generation Cost Analysis Working Group implicitly takes into account an accident frequency drop in line with additional safety measures as explained above, descriptions here are based on the 2011 assessment by the Costs Analysis Committee. Even if the 2015 assessment is used, however, discussions in this section may not change greatly.

[10] As described in Section 2-1, the Costs Analysis Committee cited an unspecified damage value for the Fukushima accident as a factor behind the uncertainty of the unit accident risk cost and noted that if the damage value increased from 5.8 trillion yen to 6.8 trillion yen, the unit accident risk cost would rise from 0.50 yen/kWh to 0.59 yen/kWh. This explanation looks insignificant from the viewpoint of

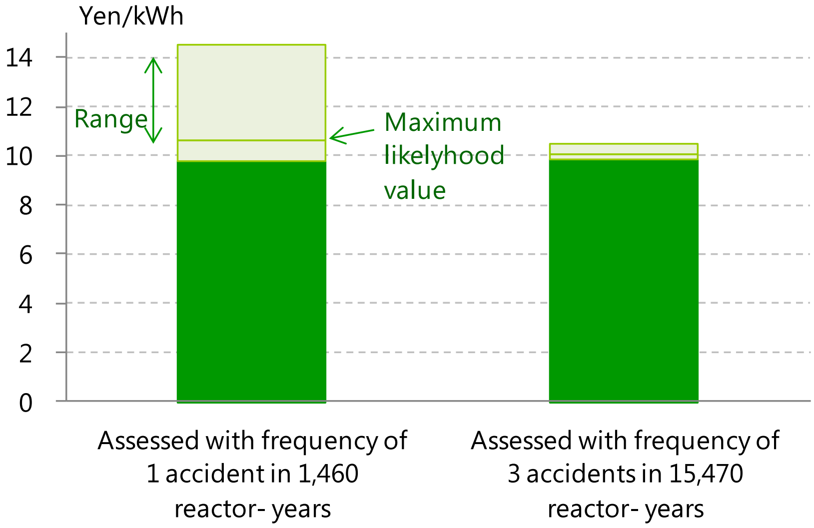

Figure 3-1 Unit nuclear power generation cost (including accident risk cost) for the accident damage value of 5.8 trillion yen

How about using the accident frequency of three in 15,470 reactor-years in the world? As the frequency increases from one to three, the uncertainty is reduced considerably[12]. The accident frequency in the 95% confidence interval comes to 4.0×10^{-5}-4.6×10^{-4}/reactor-year. The unit accident risk cost is estimated at 0.15 yen/kWh in terms of maximum likelihood value, and the unit cost ranges from 0.03 yen/kWh to 0.45 yen/kWh, indicating a more than 10-fold gap. The unit nuclear power generation cost comes to 8.4-8.8 yen/kWh, with the maximum likelihood value being at 8.6 yen/kWh. This result may not be accepted as sufficiently satisfactory. Compared with the assessment using the accident frequency of only one, however, the assessment adopting the frequency of three is far less uncertain, as seen in Figure 3-1. Given errors in power generation cost assessment, not limited to the accident risk cost, the gap or uncertainty of 0.3 yen/kWh may manage to fall into an acceptable range.

(2) How to treat “lowly frequent, great damage”

If a nuclear accident damage value and frequency are assessed in a persuasive manner, how should we interpret a contention that the risk will be higher for the lowly frequent, great loss? To what extent is it appropriate to assess the high risk in some manner and assume a higher accident risk cost than an expected damage value? When considering these questions, we must understand that the significance of the great value depends on the economic size of the responsible party. When I purchase automobile insurance, for example, damages worth millions of dollars may be too much for me but not so for an insurance company. Therefore, I may regard the compensation risk as greater than a simple expected value and the gap may allow an insurance contract to be established to benefit both the insured and insurer. Despite the fact that the automobile liability risk for me is greater than indicated by the insured amount, the risk may be converted into an accumulated insured

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the probability theory. Whether the damage value increases from 5.8 trillion yen to 8 trillion yen or 10 trillion yen, the 100-fold gap in the minimum and maximum accident frequency estimates may exert an even greater impact.

[11] In making such assessment, some people occasionally insist that it is appropriate to use the 95th percentile for assessing accident risks on the safe side. However, this is not any appropriate assessment. When the safety of nuclear or any other equipment is assessed, such safe side assessment is usually conducted, which is justified as one side from a standard value has safety with the other side having dangers. In cost assessment, however, dangers exist on both sides. As far as accident risks are concerned, their underassessment risks great economic impacts of accidents, while their overassessment risks the wrong selection of higher-cost electricity sources. In such assessment, risks should be assessed purely from the viewpoint of economic efficiency.

[12] This can be imagined in our daily life. If I carelessly cause three accidents in 20 years, I may naturally think that I could cause an accident again in several years if I fail to be alert. If I run into a person by accident for the first time in 20 years and think that I could see the person in 20 years again, it may mean that I believe in something other than the probability theory.

amount, which is greater than an expected liability.

If an electric utility can purchase some insurance to cover accident risks involving nuclear power generation from this viewpoint, the accident risks for the utility will be assessed as an accumulated insured amount. Such assessment may be adequate as far as the narrowly defined power generation costs are concerned. If a national burden as broadly defined power generation costs is to be assessed, however, the situation may be different. Given that the country's economic size is far greater than the size of an insurance company, it is not realistic for the government to pass the risks on to an insurance company. Either, it is not adequate to use a virtual insured amount for assessing a national burden involving accident risks. If the accident damage value is 10 trillion yen, the amount may not be large enough to topple the Japanese economy with annual gross domestic product worth 500 trillion yen (suppose a case where a 1,000-dollar loss emerges at a very low frequency for a household with about 50,000 dollars in annual income). Therefore, the risks may be assessed as close to an expected damage value.

Even if the damage value for the Fukushima accident is limited to around 10 trillion yen, however, the damage value for a future accident may not be the same. As far as there is the possibility of the damage value exceeding the country's economic size by far, there may be some premium for such high damage. However, such premium may not be converted into any monetary value. In principle, it cannot become subject to assessment (see the previous paper4) for details). The most appropriate method for assessing a national burden involving nuclear accidents may be to compute and use an expected accident damage value.

(3) How to assess an accident frequency

As noted in (1) above, the accident frequency assessment is the most uncertain when accident risks involving nuclear power generation are assessed. How should we assess the accident frequency?

It is widely recognized that the concept of risks we have in our daily life is not necessarily based on reasonable decisions. For example, D'haeseleer18) gives the following explanation about comparison between aircraft and automobile accidents: One aircraft accident accompanied by 400 deaths is viewed as more serious than 400 automobile accidents accompanied each by one death. Whether a close friend is killed in an automobile or aircraft accident, however, the death is cruel for anyone. Due to such daily sensory gap, most people, probably including Prof. D'haeseleer, feel a vague risk when boarding an aircraft more strongly than when getting in an automobile despite the fact that getting in an automobile is riskier than boarding an aircraft. It is very understandable that such risk perception gap regarding nuclear power generation becomes particularly remarkable occasionally. Meanwhile, however, it is true that nuclear power bears a great risk which must not be underestimated.

What data can we use for calculating an accident frequency? The abovementioned probabilistic risk assessment (PRA) is an attempt to assess the frequency as objectively as possible. The PRA assesses the occurrence probability of each event for all theoretically conceivable accident paths and estimates the accident frequency as their total. If there is any reason for concluding the PRA as inadequate, the reason itself may have to be reassessed as well to give more adequate results. As noted in the appendix, even if we do not believe in such scientific method, the reason for refusing to believe in the science must be assessed anew. We must first make efforts to improve the PRA accuracy in order to make an accurate assessment. PRA results and limited information on an actual accident frequency are all information that can be used for assessing the accident frequency.

If we have no nuclear power plant operation experiences, we may depend only on PRA data for assessing accident risks. There may be no reason for asserting the nuclear accident frequency as lower or higher than indicated by the PRA. As we actually have experiences with nuclear power generation over decades and with a limited number of accidents, we can use such experiences to assess and revise PRA data. As an actual accident frequency looks higher than indicated by PRA assessment data, many people are concerned that a real accident frequency may be higher than suggested by the PRA assessment. From this viewpoint, it may be adequate for Lévêque to have attempted to make the most reasonable assessment by interpreting PRA results as an integration of our scientific knowledge and by using the PRA results and an actual accident frequency, using a Bayesian statistics approach. The details of this approach are given in the appendix.

The next problem is how to treat the effects of additional safety measures. For example, the containment failure frequency (CFF) of 2.1×10^{-4} per reactor-year is given through the PRA for Unit 3 of Hokkaido Electric Power Co.'s Tomari Nuclear Power Station[27)]. The CFF is for the case without additional safety measures taken after the Fukushima accident and may be compared with the actual accident frequency of one in 1,460 reactor-years. Actually, however, Japanese nuclear power stations have implemented additional safety measures based on the Fukushima accident. As far as these measures are designed to reduce the accident frequency, it may be unreasonable to view the frequency predicted after the additional safety measures as unchanged from that before these measures. The PRA may be useful to some extent for assessing the degree of the frequency reduction. However, we have no actual data on the accident frequency after the additional safety measures. How to treat actual data and PRA results may have to be studied further.

(4) Securing safety and accident risk cost

Based on continuous study, the accident risk cost should be assessed and updated appropriately. Our purpose here is to reduce the uncertainty of the accident frequency as much as possible. Let's look at the assessment range in Figure 3-1 anew. The actual accident frequency of one in 1,460 reactor-years given in the left of the figure is the only data to convince us of high frequency. Even if an accident damage value becomes considerably greater than the assumption by the 5.8 trillion yen, therefore, it may be difficult to have clear reasons for asserting that the damage value increase would exert any significant impact on the unit nuclear power generation cost, as the lower limit for the frequency is considerably small. On the other hand, if the assessment range becomes narrower, it may be possible to assert that accident risk bears no significant impact[13]. If the accident frequency assessment range is narrowed in some way to the degree indicated on the right side of Figure 3-1, may we conclude that accident risks would never be any major matter of concern for the use of nuclear energy? A clear answer may be no. This is because utmost efforts must be made to avoid any nuclear accident irrespective of whether an accident would make small or great contributions to the unit nuclear power generation cost.

Assume an accident damage value at 10 trillion yen. If the accident frequency is one in 2,000 reactor-years (one in 40 years for 50 reactors), the unit accident risk cost will be 0.7 yen/kWh. If the frequency is one in 100,000 reactor-years (one in 2,000 years), the cost may be only 0.01 yen/kWh. We must pay special attention to the fact that if a Fukushima-class accident occurs once in 40 years, nuclear energy use must be avoided irrespective of how much the cost would be. If additional safety measures can reduce the accident probability significantly, the accident risk cost would have no significant impact on the economy of nuclear energy. On the other hand, if they fail to reduce the accident probability, we should never make use of nuclear energy. In either case the estimated cost is not relevant. What we should consider when deciding whether nuclear energy should be accepted would not be the accident risk cost, but the problem of whether safety could be secured.

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[13] This does not mean that we would not have to think about an accident risk cost in any case. As noted in the appendix, if a Fukushima-level accident occurs once or twice in the future, the accident frequency as a subjective probability at least in terms of Bayesian statistics will remarkably increase.

4. Conclusion

This paper summarized existing assessments on an accident risk cost for nuclear power generation and analyzed how the problem should be treated in the future. The biggest problem with the assessment of the accident risk cost is the uncertainty of accident frequency. No method for assessing the frequency has yet been established and it will have to be studied further in the future.

However, it is indispensable to fully reduce the accident probability with safety measures in order to continue using nuclear energy. Under this premise, the accident risk cost may have no major impact on the economics of nuclear power. When nuclear and other electricity sources are compared, in general, cost assessments may become a strong ground for deciding which source is superior. However, the grounds for any decision may not be limited to the cost assessments. We may have to consider other factors as well and make comprehensive decisions. In fact, whether it is appropriate for Japan or any other country to implement nuclear power generation in the future depends on whether we can believe that sufficient safety can be secured. This point should be given sufficient consideration before the economy of nuclear power generation is analyzed.

Appendix: Assessment of accident probability using Bayesian statistics

(1) Subjective probability and Bayesian statistics

The probability is understood as an event occurrence frequency. If an event occurs five times when 100 trials are conducted, the event probability is given as 5÷100=0.05. Under such understanding, trials must be conducted to assess an event probability. Actually, however, we discuss the probability of what could not be repeated. As an example, Lévêque cites Blaise Pascal's argument for the probability of the existence of God as an event that cannot essentially be repeated. Even without referring to Pascal, we know that we consider the possibility of a specific event occurring on the specific day of tomorrow, or the possibility of an event that cannot be repeated, in our daily life. Such probability differs from an objective occurrence probability involving repeated trials and is called a "subjective" probability. Bayesian statistics is understood as handing the "subjective probability."

Bayesian statistics estimates a probability or probability distribution for an event by using the formulation of conditional probability to process data for the event. If an event occurs five times when 100 trials are conducted, the event's occurrence frequency is 0.05 and the event's occurrence probability is "estimated" at 0.05. Estimated here is 0.05 as the maximum likelihood value of the probability. The event might have occurred five times accidentally despite the probability of 0.03. Or, it might have occurred only five times accidentally despite the probability of 0.1. If we were to assess the probability more accurately, we would conduct more trials. If the event occurs 47 times when 900 more trials are conducted, the event's (subjective) probability will rise from 0.05 to 0.052[14].

In such simple trial case, the maximum likelihood value of the subjective probability eventually matches a simple event probability. The subjective probability theory makes a difference when we have some information differing from an event occurrence probability. If an event occurs five times when 100 trials are conducted after we assessed the maximum likelihood value of the event probability as 0.1 based on the past information, our subjective probability will fall from 0.1 to between 0.1 and 0.05 due to the trial experience. The first advantage of using this approach is that it can conduct a comprehensive assessment using two different kinds of information -- our prior information and an event frequency based on a new experience. The second advantage is that even if the frequency of an event in a new experience is limited with no statistically significant result expected, prior information can be used together to conduct an assessment of which the uncertainty is smaller. For small municipalities where stable data about deaths are difficult to collect, for example, the Ministry of Health, Labour and Welfare of Japan uses data for wider areas including these small municipalities as prior information to conduct more stable assessments about the death rate under the Bayesian estimation approach[28)].

For a specific computation process for the Bayesian estimation, see relevant books[15]. A "prior distribution" (probabilistic distribution of parameters indicating the abovementioned prior information) is multiplied by a likelihood function (a conditional probability of actual data occurring when parameters take their values) and standardized to calculate a posterior distribution (an eventual probabilistic distribution of parameters).

(2) Assessment of accident frequency using existing data

Here, I would like to consider how best to assess nuclear accident frequency (an accident occurrence probability per reactor-year). Table A-1 indicates all information we now have for the assessment.

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[14] Attention must be paid to the fact that the subjective probability is estimated with our information used to the maximum extent based on an "objective" methodology. In this sense, this probability differs from the "subjective" certainty like a risk perception regarding an aircraft accident as discussed in Section 3-1-2.

[15] E.g.: Shigemasu, K., "Guide to Bayesian Statistics," University of Tokyo Press

Table A-1 Accident frequency and PRA assessment results

	Operation experience, reactor-years	Number of accidents	Accident frequency, times per reactor-year	95th percentile
Actual accidents (world)	15,470	3	1.9×10^{-4}	—
Actual accidents (Japan)	1,460	1	6.8×10^{-4}	—
PRA assessment results (U.S. CDF)	—	—	6.5×10^{-5}	2.0×10^{-4}
PRA assessment results (CFF for Tomari # 3)	—	—	2.1×10^{-4}	7.7×10^{-4}

Sources: NRC[17)], Lévêque [16)], Hokkaido Electric Power[27)], author-prepared data

Here, attention must be paid to the fact that the U.S. PRA assessment result is for the CDF of which about one-tenth is the LERF. In Japan, PRA assessment was made for each reactor after the Fukushima accident. An example here is the result for Unit 3 of the Hokkaido Electric Power Co.'s Tomari Nuclear Power Station. However, the PRA assessment result for Tomari Unit 3 was given before additional safety measures. Therefore, attention must be paid to the fact that the accident occurrence probability for the following assessment is that for a case where additional safety measures are not implemented. Anyway, our challenge here is to assess the accident risk by using only PRA and the information on actual operating experience.

(3) Lévêque approach and its application to Japan

Lévêque used the NRC-given CDF value and its 95th percentile to approximate the prior distribution in the Bayesian estimation with the following beta distribution:

$$\pi_0(p) = Be[st, s(1-t)] = \frac{p^{st-1}(1-p)^{s(1-t)-1}}{B(st, s(1-t))} \tag{1}$$

Here, *p* stands for the accident frequency, *t* for a parameter (6.5×10^{-5}) indicating an expected frequency, *s* for a parameter (24,869) indicating the strength of the distribution, and *B* for the beta function.

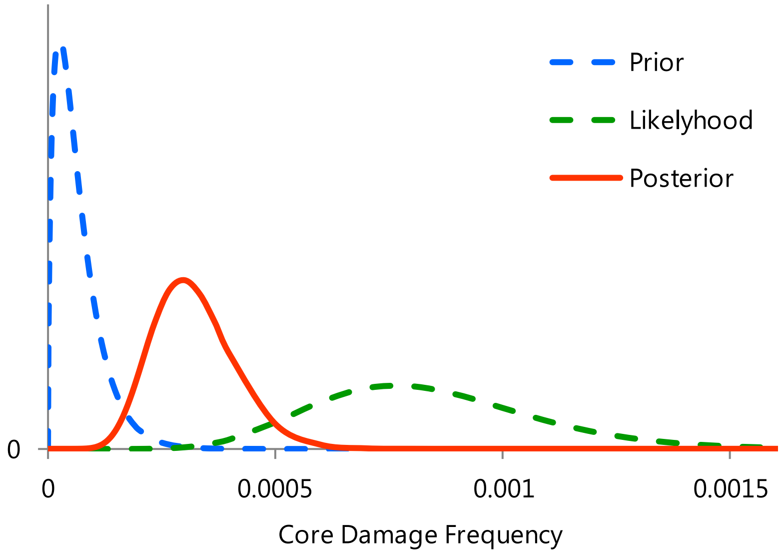
As actual accident occurrence data against this prior distribution, Lévêque used 14,400 reactor-years representing the past nuclear plant operation in the world for *n* and 11 core damage accidents for *y*. The core damage frequency comes to 7.6×10^{-4} per reactor-year, some 10 times as high as the PRA-based frequency (6.5×10^{-5} per reactor-year). Bayesian updating determines the posterior distribution of the accident frequency, expressed as a beta distribution as follows:

$$\pi_1(p \mid y) = Be[st + y, s(1-t) + n - y] \tag{2}$$

Based on this, the expected accident frequency is given as follows:

$$E(p \mid y) = \frac{y + st}{n + s} \tag{3}$$

As the above data are assigned to the equation, the average accident frequency based on actual operation comes to 3.2×10^{-4} per reactor-year. In this way, Lévêque used the lower value of PRA-based accident frequency and the higher value of actual accident frequency to calculate a comprehensively assessed accident frequency as an intermediate value between them (Figure A-1).



(Note) In this figure, the likelihood function as well as prior and posterior distributions are normalized at 1.

Figure A-1 Lévêque's CDF assessment

The problem here is that if we adopt the average CDF at 3.2×10^{-4} per reactor-year as the point estimate, this value slips below the lower limit of the 95% confidence interval of the CDF estimated only from the actual data -- 11 accidents in 14,400 reactor-years. This means that if the CDF is 3.2×10^{-4} per reactor-year, the probability of an accident occurring 11 or more times in 14,400 reactor-years is very low (standing at 0.8% as described in Section 2-2-5). What's happening here is indicated by Figure A-1. Intersections between the distribution of PRA data and the distribution estimated from data for the 11 actual accidents are very small, meaning that the two distributions almost conflict with each other. The conflict indicates that the PRA data for the prior distribution had been unreliable, that actual data had been inappropriate, or that the prior distribution and actual data had been for different subjects.

It is conceivable that the method for counting 11 accidents in 14,400 reactor-years was inappropriate. Lévêque explained that most of the 11 accidents occurred in the initial phase of nuclear energy use before safety was improved with operation experiences accumulated. As explained in Section 2-2-5, D'haeseleer said that only five out of the 11 accidents should be counted in line with the definition of the CDF. As noted in the footnote for the section, core damage at Units 1 to 3 of the Fukushima Daiichi Nuclear Power Station should not be interpreted as representing three independent accidents. If the number of actual accidents is estimated at lower than 11 with these factors taken into account, the likelihood function in Figure A-1 comes closer to the PRA distribution, with the abovementioned problem eased. Meanwhile, there is a problem regarding the reliability of PRA data. It cannot be denied that the actual CDF could have been higher.

Despite these problems, as far as we have no information other than PRA and actual data, it may be necessary to consider this method for combining these data. The following indicates the result for the case where we follow this method in line with information we have.

As noted by D'haeseleer, we should use the LERF instead of the CDF for assessing accident risks. However, the revision by D'haeseleer exogenously multiplied a value after Bayesian updating by the CDF/LERF ratio. In this sense, the revision has yet to undergo Bayesian updating. This paper directly assesses the LERF leading to accident damage. By counting the number of large accidents rather than the number of damaged cores, we can consider the Fukushima accident as a single one to avoid the problem of the conditional probability as described in the footnote for Sector 2-2-5.

Based on these points, the LERF accident frequency is assessed anew as follows: First, the prior distribution is assumed as Equation (1) according to the NRC. Here, *t* is put at 6.5×10^{-6} with consideration given to the CDF/LERF ratio. The problem is how to set *s*. Lévêque set *s* to lead the 95th percentile of the prior function to match the 95th percentile of the PRA. If the CDF/LERF ratio is fixed at 0.1, *s* may be set to lead the 95th percentile to become 0.1-fold, as is the case with *t*. However, the CDF/LERF ratio is expected to vary. In the past, ExternE had put the ratio at around one-fifth (about 0.19). However, the ratio has been assessed as lower and given at less than 0.1 over the recent years. Here, *s* is set to lead one-fifth of the 95th percentile of the CDF to be 95% of the LERF (specifically, *s* =32,500), taking into account the ExternE assumptions. Given the world's nuclear reactor operation experiences (*n*=15,470) and the accident frequency (*y*=3) in Table A-1, the posterior distribution and the expected accident frequency are computed with Equations (2) and (3) and the point estimate (average) of the LERF is finalized at 6.7×10^{-5} per reactor-year. The result is some four times as large as the D'haeseleer assessment given in Section 2-2-5. While D'haeseleer effectively put the actual accident frequency corresponding to the LERF at 5 cases ×0.1 (=0.5 case), this paper put the frequency at 3 cases. As a result, this paper's assessment is larger. The LERF in the 95% confidence interval comes to 1.5×10^{-5}-1.6×10^{-4} per reactor-year.

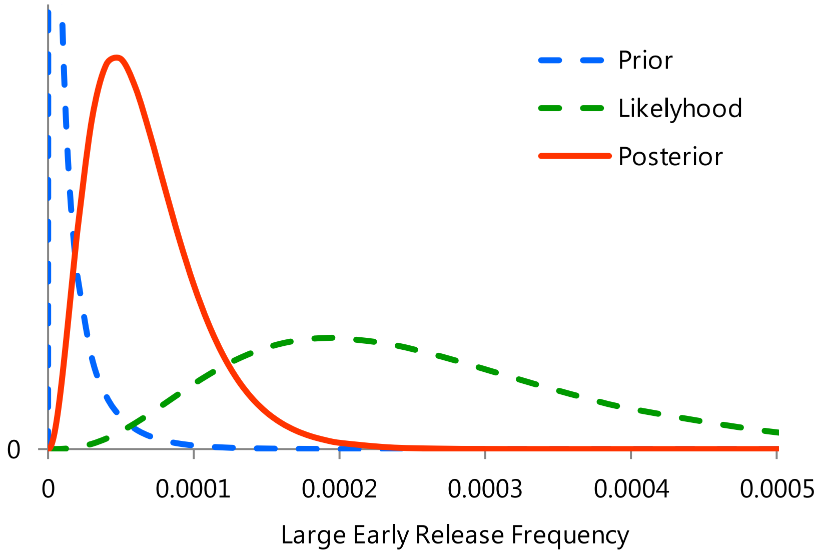


Figure A-2 LERF assessment

The point estimate of the LERF at 6.7×10^{-5} per reactor-year is slightly larger than the LERF's 2.5 percentile at 4.0×10^{-5} per reactor-year as estimated only from actual data. In this sense, gaps between data for this estimation may be less than for the abovementioned Lévêque estimation. However, the point estimate is still larger than the 97.5 percentile of the prior distribution. Therefore, believing in the LERF as the point estimate may amount to doubting the PRA result. One way to address this problem is to revise actual data. For example, the number of nuclear accidents at three may be revised downward to two, with the TMI accident excluded. Or, the Fukushima accident may be excluded as an incident attributable to design errors, limiting the assessment targets to reactors that were duly designed as assumed in the PRA, as in the IER estimate described in Section 2-3. Another approach is to develop a model including factors for doubting the reliability of PRA data.

In the abovementioned equation formulation, actually, the location of the point estimate of the LERF between the PRA result and the actual accident frequency depends on the intensity parameter of *s* as estimated from the PRA result (95th percentile). In this approach, the PRA result is assessed as more accurate if the PRA result range is narrower, with the 95th percentile being closer to the average. Therefore, the LERF computation result comes closer to the PRA result rather than the actual accident frequency. The PRA assessment range integrates ranges of individual events through the computation process. When we doubt the PRA result and attempt to revise PRA data, what we call into question may be the reliability of the PRA assessment approach rather than assessment ranges for individual events for the PRA. In other words, we feel vague, lingering fears about a nuclear accident because we firmly believe that events that are "not expected" in PRA could always occur. Actually, the possibility of a greater-than-expected earthquake motion has been appreciated as a "residual risk" since before the Fukushima accident. The possibility of an unexpected event leading to a grave nuclear accident is not limited to earthquakes. The most essential fears we have in regard to nuclear energy are about dangers that would come from the outside of what we understand as a nuclear power generation system. We may have to assess this factor to explain our fears about nuclear energy.

From this point of view, we can formulate a new equation. Let me specify details in a separate paper and provide an outline here. First, a binary variable dubbed ω may be devised for an assumption that while $\omega=0$ indicates the PRA assessment as effective, $\omega=1$ suggests that an external factor that is not covered in the PRA would cause an accident. We cannot identify this external factor in advance. So, we have no information on the occurrence probability for the external factor. Then, α_0 is given as the prior reliability of the PRA to set the value of the integral at α_0 for the $\omega=0$ subspace and at $(1-\alpha_0)$ for the $\omega=1$ subspace in the prior distribution. Specifically, the prior reliability of α_0 is set at 0.8, indicating that we rely on the PRA as a special science to some extent.

After Bayesian updating using actual data, $\alpha=0.29$ is given as an example of the posterior reliability. In this case, the reliability of the PRA declines substantially due to the prior distribution's wide deviation from actual data. The following figure indicates the final posterior distribution given by the PRA prior and posterior distributions, the posterior distribution coming from external factors, and the weighted average.

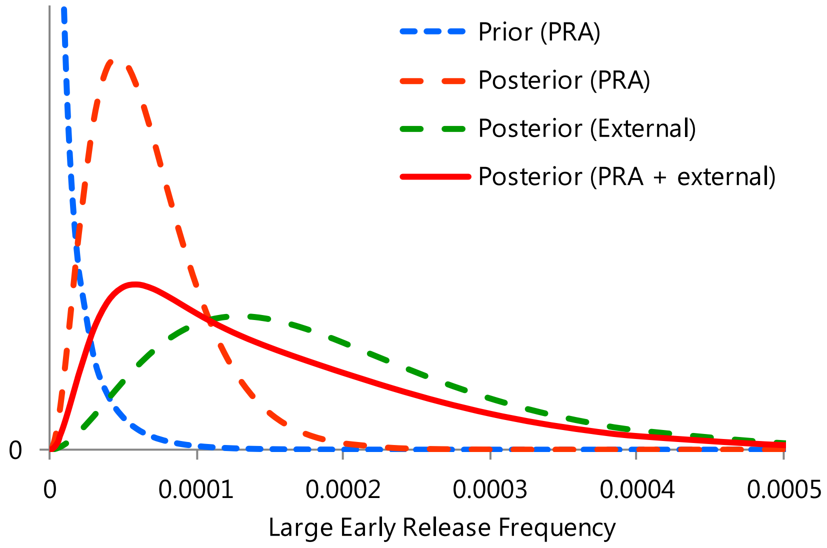


Figure A-3 LERF assessment giving consideration to external factors

(4) Accident frequency assessment: Japanese case

The abovementioned accident frequency assessment method is applied to Japan as follows: First, assumptions regarding the actual accident frequency include $n=1{,}460$ and $y=1$ as described above. Electric utilities conducted their respective PRA assessments after the Fukushima accident. Cited here are data from Hokkaido Electric Power's assessment of Tomari Unit 3[27)].

Japan's PRA assessments after the Fukushima accident generally targeted the containment failure frequency (CFF)[16] instead of the LERF. Here, the CFF is subjected to assessment. Tomari Unit 3 data are given in Table A-1. Beta distribution parameters are given as $t=2.1\times10^{-4}$ and $s=2{,}710$ to meet the average and 95th percentile of the data.

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[16] As the containment vessel damage is a necessary condition, rather than a sufficient condition, for an early massive radiation release after an accident, the CFF is generally larger than the LERF. The PRA assessment of the CFF is called "Level 1.5 PRA" against "Level 2 PRA" for assessing the LERF.

As these parameters are used for creating the posterior distribution in line with the Lévêque approach, the expected CFF in the posterior distribution comes to 3.8×10^{-4}. As Bayesian estimation is conducted with the prior reliability of the PRA put at 0.8 as explained in the previous section, the posterior reliability comes to 0.88 and the expected CFF to 4.4×10^{-4}. In this case unlike the previously cited case, the assumed one accident in 1,460 reactor-years does not injure the reliability of the PRA but increases it. The 95% confidence interval is indicated as 3.2×10^{-5} to 1.0×10^{-3} with the error factor (EF), the square root of the ratio of the upper and lower limits in the confidence interval, standing at 5.7, reducing the error range considerably from the case (EF=12.1) where the PRA is not taken into account.

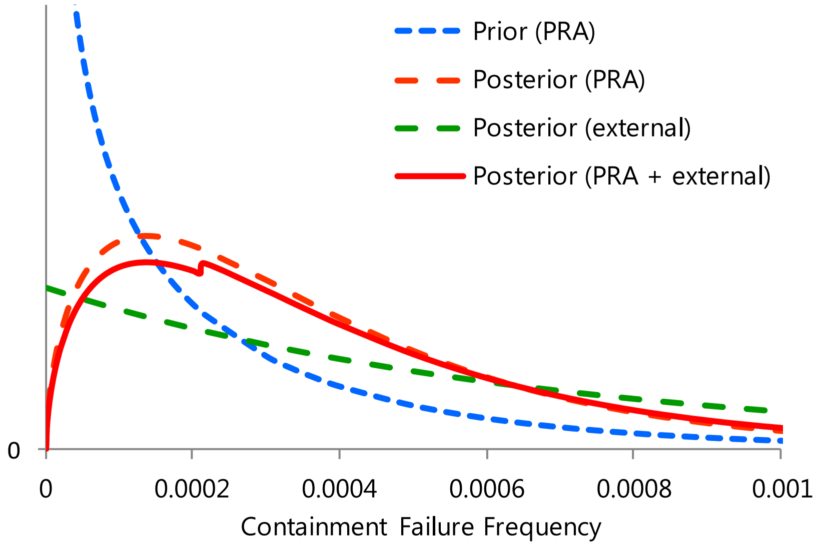

Figure A-4 CFF assessment giving consideration to external factors

In this example, results for the case where consideration is given to external factors do not differ so much from those for the case without such consideration. As the accident frequency of *y* is increased, however, their gap widens. As indicated in Figure A-5, as *y* increases, the CFF value giving consideration to external factors rapidly grows larger than the CFF without such consideration, coming closer to the simple accident frequency. If a major accident occurs again and again after nuclear reactors restart operation, most people may no longer rely on the PRA, with the CFF assumed by people coming closer to the simple accident frequency. As indicated by Figure A-5, we can express such conditions more appropriately by giving consideration to external factors.

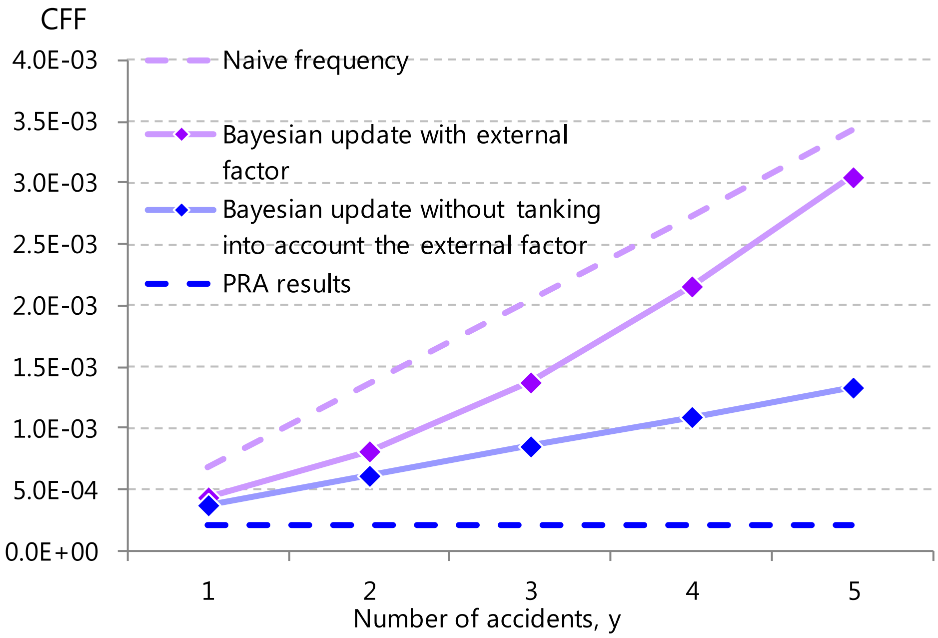

Figure A-5 Effects of changes in accident frequency (y)

(6) Conclusion

By using the Bayesian statistics approach, as explained above, we can estimate the accident frequency with consideration given to both the PRA-assessed accident frequency and the actual accident frequency. This can ease the uncertainty of the assessment to some extent. However, the result may change greatly depending on the prior distribution and the estimation method. Further study may be required on appropriate methods.

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Contact: report@tky.ieej.or.jp